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LIGHTNING PROTECTION OF STRUCTURES AND PERSONAL SAFETY

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1. INTRODUCTION

This paper is concerned with a number of topics related to the lightning protection of structures and personal safety, as outlined next. Lightning incidence to areas and structures is discussed. A review of lightning protective systems of structures, whose function is to intercept lightning and safely direct its current to ground, is given. Small open shelters commonly found on golf courses, in parks, and elsewhere are discussed from the point of view of safety from lightning. Early warning of the lightning activity is briefly considered. The behavior of grounding systems under direct lightning strike conditions, particularly ground surface arcing, is discussed.

2. LIGHTNING INCIDENCE TO AREAS AND STRUCTURES

Ground flash density, N_g, defined as the number of cloud-to-ground flashes per square kilometer per year, is the primary descriptor of lightning incidence to areas. This parameter has been estimated from records of lightning flash counters and lightning locating systems, and can potentially be estimated from records of satellite-based optical or radio-frequency radiation detectors. The observed variation in ground flash density from one region to another in the contiguous United States is about two orders of magnitude. Many flashes strike ground at more than one point. The correction factor for measured values of ground flash density necessary to account for multiple channel terminations on ground is about 1.7.

It is often said that lightning never strikes the same place twice. The validity of this saying depends on what is actually meant, as discussed next. The most common type of lightning discharge between a thundercloud and Earth's surface, which accounts for 90% of all lightning discharges involving ground, begins in the cloud. Before the brilliant lightning channel bridges the gap, a lightning process called a leader takes place. This process creates a downward branched, low-luminosity channel, not observable with a naked eye or with an ordinary photographic camera. The leader channel extends from the cloud in search of a termination point on the ground. If we consider a terrain that is essentially flat and geologically uniform, the lightning termination point on ground can be viewed as random. In this case, the saying "lightning never strikes the same place twice" would be essentially true. Indeed, a small area of 1 square meter in an open field in Florida is struck by lightning on average once every 100 millennia. Thus, if you saw a lightning strike to that 1 m^2 area, another one could be expected in 1000 human generations or so, which is for all practical purposes equivalent to never. It is worth noting that each lightning flash is typically composed of 3 to 5 component strokes many of which retrace the same channel to ground. However, these component strokes occur within a second or less and can be detected by naked eye only as the flickering in luminosity of the lightning channel.

In reality, ground is not homogeneous and, as a result, the descending lightning leader will be attracted to some terrain features more than to others. Grounded metallic objects dominating a region are more likely to be struck by lightning than the surrounding ground or lower structures nearby (this is how lightning rods work). In general, the taller the object, the more often it is struck. For example, a 30-m tower located in Florida is struck by lightning, on average, once in 3 to 4 years, while a 60-m tower is struck on average once every year. As the height of an object increases beyond 100 m or so, a different type of lightning discharge to this object can occur, in addition to the type described above. This additional type of lightning also involves a leader process, but the leader channel originates on the object and extends toward the cloud. Clearly, in this case the strike point is predetermined, in contrast with the case of lightning initiated by a descending leader. If the object is very tall, such object-initiated lightning may occur literally dozens of times every thunderstorm season. For example, the Ostankino TV tower in Moscow, Russia, which is 540 m high, experiences about 30 lightning strikes per year. If this tower were relocated to the Tampa Bay area, Florida, where lightning activity is 3 to 4 times more intense, it would experience 90 to 120 strikes per year.

In summary, from a lightning standpoint the saying "lightning never strikes the same place twice" is certainly not true. It does strike its preferential targets such as tall towers over and over again. However, from the standpoint of a small area in a large open field the saying is essentially true.

When the incidence of downward lightning to a ground-based object is estimated, it is common to ascribe a so-called equivalent attractive (or exposure) area to that object. The attractive area can be viewed as an area on flat ground surface that would receive the same number of lightning strikes in the absence of the object as does the object placed in the center of that area. In other words, in computing lightning incidence to a structure, the structure is replaced by an equivalent area on ground. For a house (or other similar structure) located in a region characterized by a moderate ground flash density $N_g = 4$ $km^{-2}\ yr^{-1}$ and having an area of 10 x 20 m^2 and a height of 5 m so that the equivalent attractive distance (assumed to be roughly twice the height) is about 10 m, the equivalent attractive area A is about 30 x 40 = 1200 m^2. Such a house is expected to be struck by lightning $(1200\ m^2)\ (10^{-6}\ km^2\ m^{-2})\ (4\ km^{-2}\ yr^{-1}) = 4.8 \times 10^{-3}$ times a year, or about once every 200 years. Another way to think of this lightning incidence is that, in this region, one of 200 houses will be struck each year, on average.

The probability of a structure, represented by its equivalent attractive area A, to be struck exactly 0, 1, 2, 3, …n times in T years can be estimated using the Poisson probability distribution,

$$p(n) = (Z^n/n!)\exp(-Z) \qquad (1)$$

where $Z = AN_gT$, the average number of strikes expected over T years, provided that N_g remains constant. Continuing the previous example, Table 1 gives the number of houses, out of a total of 200, expected to be struck by lightning n times over T years, as predicted by equation (1). Each number is found as the product of the total number of houses, 200, and p(n) from equation (1) with subsequent rounding off to nearest integer. In two cases (n = 1; T = 80 yr and T = 100 yr) the rounded off number was increased by 1 in order to insure that the sum of numbers in each row is 200, the total number of houses considered. It follows from Table 1 that, for example, over a 60-year period 150 houses will not be struck at all, 50 (43 + 6 + 1) will receive at least one strike, 6 houses will be struck twice, and one house even three times. If N_g = 12 km^{-2} yr^{-1}, characteristic of some areas in Florida, then over a period of 60 years only 84 houses out of the 200 will not receive any lightning strikes, and 11 houses will be struck 3 times or more.

Table 1. Number of houses out of a total of 200 (percentage if divided by 2) expected to be struck by lightning n times over T years (N_g = 4 km^{-2} yr^{-1}; A = 1200 m^2).

Number of years of observation, T	Number of times struck by lightning, n				
	0	1	2	3	>3
10	191	9	0	0	0
20	181	17	1	0	0
30	173	25	2	0	0
40	165	32	3	0	0
50	157	38	5	0	0
60	150	43	6	1	0
70	143	48	8	1	0
80	136	53	10	1	0
90	130	56	12	2	0
100	124	60	14	2	0

3. GENERAL INFORMATION ON LIGHTNING PROTECTION OF STRUCTURES

Basically, a lightning protection system for an ordinary structure includes (1) air terminals, (2) down conductors, and (3) ground terminals. These three elements of the system must form a continuous conductive path (actually at least two paths) for lightning current, with all connections between the elements typically being accomplished by bolting or welding. The function of such a system is to intercept lightning and safely direct its current to ground. If a structure has a metal roof and the thickness of this roof is 3/16 in. or greater, the roof can play the role of the air terminals. The structural metal framework (including metal support posts) can play the role of down conductors if it is electrically continuous. Sometimes the ground terminal is made of a buried bare conductor encircling the structure (also called a loop conductor). Such grounding is beneficial in that it additionally serves to intercept ground surface or underground electrical arcs (see Section 6 below) that may develop toward the structure from a nearby object (such as a tree) struck by lightning. The closer the structure approaches a Faraday cage, the better its interior is protected from lightning effects. More details on lightning protection of small shelters are found in Section 4.2.

4. SMALL SHELTERS AND SAFETY FROM LIGHTNING

Small open shelters are common on golf courses, athletic fields, parks, roadside picnic areas, schoolyards, and elsewhere. Many of these shelters are built to protect against rain or sun, not lightning. Although there is no such thing as a lightning-proof small outdoor shelter, a properly designed and installed lightning protection system may make a difference. Sometimes the difference is between life and death. The following discussion of small shelters from the point of view of safety from lighting is based on paper written by the author in collaboration with R. Kithil for Golf Course Management Magazine (Kithil and Rakov 2000).

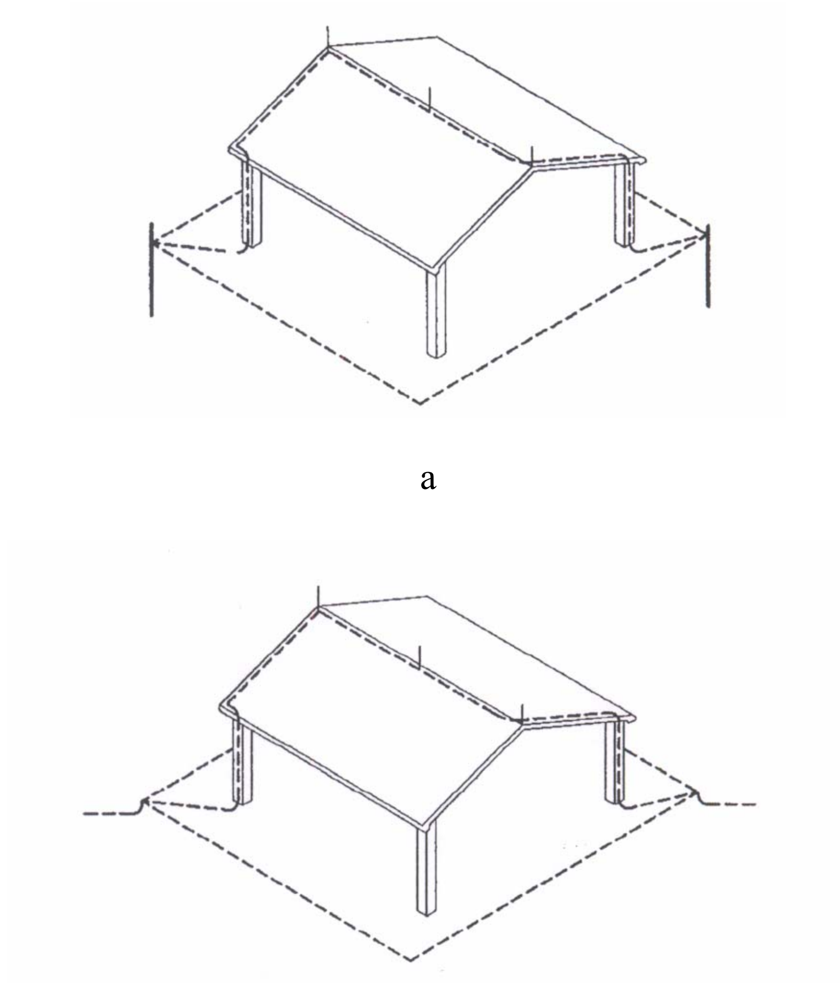
4.1 Shelters Unprotected from Lightning

In the absence of the three-element lightning protection system described in Section 3 above, the structure should be considered unprotected from lightning. Small shelters without lightning protection should be avoided during thunderstorms, particularly if they are located in high areas (such as on a golf course hill) or near a tree or a small group of trees dominating the area. If there is no better choice only shelters in relatively low areas should be used, preferably surrounded by a large number of trees of approximately the same height. A disclaimer statement should be posted on each unprotected shelter by the organization running the outdoor facility. Such a disclaimer should include a clear statement that the structure does not offer protection from lightning. It would also be appropriate here to include a concise guide for personal safety from lightning (e.g., Holle et al. 1999).

4.2 Shelters Protected from Lightning

A small shelter equipped with a properly designed and installed lightning protection system provides reasonable protection from lightning. It is essential, however, that a person inside the shelter does not touch any element of the lightning protection system and tries to position himself or herself at approximately the same distance from all down conductors. A small shelter, even one protected as described here, should be viewed as the last resort option. Better protected shelters such as large buildings and all metal vehicles should be sought instead when possible.

A properly protected small shelter should have at least one air terminal (or equivalent), at least two down conductors on two diagonally opposite sides of the structure (four down conductors provide better lightning protection than two conductors), and ground terminals connected to the down conductors. Two designs for ground terminals in common soils can be recommended. The first one (see Fig. 1a) includes vertical ground rods (not less than ½ in. in diameter and not less than 8 feet long), at least one for each down conductor, interconnected by a loop conductor buried at least a few inches under the earth's surface. The second design for ground terminals (see Fig. 1b) includes horizontal conductors, at least one for each down conductor, buried at a depth of not less than 2 ½ feet and extending away from the shelter for at least ten feet beyond the roof dripline. It also employs a loop conductor. In both designs, the addition of a buried metal mesh within the shelter perimeter (rebar of the steel-reinforced concrete floor can be used too), connected to the ground terminals, will further reduce the lightning hazard for people inside the shelter.



a

b

Fig. 1. Two recommended designs for lightning protective systems of small shelters.
a – vertical ground terminals, b – horizontal ground terminals.

An alternative lightning protection system consists of grounded overhead wires suspended above the shelter on separate poles. The loop conductor mentioned above can be employed here too.

Rod-type air terminals are usually solid (minimum diameter 3/8 in.) or tubular (minimum diameter 5/8 in., minimum wall thickness 0.033 in.) copper rods at least ten inches high. Air terminals should be placed on ridges of pitched roofs and around perimeter of flat roofs or gently sloping roofs at intervals not exceeding 20 ft. The distance from each end of the ridge to the nearest air terminal should not exceed 2 ft. Down conductors are usually in the form of stranded cables (minimum 17 AWG copper or 14 AWG aluminum). No bend of a conductor should form an included angle of less than 90 degrees, nor should the radius of a bend be less than 8 in. Down conductors should be covered with insulating material resistant to impact and climate conditions to a height of at least 8 feet above ground. Air terminals and down conductors can also be made of aluminum. Vertical ground rods are typically made of copper-clad steel or solid copper, and horizontal conductors are typically stranded copper cables. Aluminum conductors should not be closer than three feet to the earth for corrosion reasons. Bimetallic connectors should be employed to join aluminum conductors to copper conductors.

It is generally possible to find a local company that installs lightning protection on buildings and trees. Look in the Yellow Pages for “Lightning Protection” and “Electrical Contractors.” These companies should follow the “Standard for the Installation of Lightning Protection Systems” (NFPA 780), which includes a one-paragraph section devoted specifically to shelters (Section E-1.1, P. 32). The Underwriters Laboratories guideline is similar and is called “Installation Requirements for Lightning Protection Systems - UL96A.”

5. EARLY WARNING OF LIGHTNING ACTIVITY

Timely warning of a lightning threat is crucial for personal safety. If thunderstorms are predicted in the area, it might be better not to plan or to postpone outdoor activities such as golfing, boating, and hiking. Dark clouds should generally be viewed as potential lightning producers and as a signal to consider termination of outdoor activities. Any time that visual (flashes) or audible (thunder) indications of a thunderstorm exist, moving in or remaining in reasonably safe shelters, such as large buildings and all metal body cars, should be considered. The distance to the lightning can be estimated by counting the number of seconds between the flash and the thunder and dividing the result by 3 (to obtain kilometers) or by 5 (to obtain miles). For example, if the time interval between the flash and the thunder is 30 s, the lightning is approximately at a distance of 10 km or 6 miles. A typical thunderstorm covers this distance in 15 minutes or so. However, many lightning discharges strike ground at more than one point, with separation between the strike points (produced within less than a second) being up to several kilometers (e.g., Rakov et al. 1994). An AM-radio, tuned to the low end of the broadcast band (550 kHz), acts as a primitive lightning detector responding by periodic static “crashes” to electromagnetic radiation pulses produced by lightning discharges. The U.S. National Lightning Detection Network (NLDN) continuously provides nationwide information on the cloud-to-ground lightning activity in nearly real time.

6. GROUND SURFACE ARCING

When lightning with a peak current of 30 kA strikes a structure whose effective grounding impedance is 100 Ω, the electric potential of the grounding system with respect to remote ground is about 3 MV. This is likely to be sufficient to produce electric breakdown in the soil and particularly along the ground surface, so-called ground surface arcing. Ground surface arcs, which may pose a serious threat to persons standing near the object struck by lightning, have been studied by Fisher et al. (1994) and Rakov et al. (1998).

The percentages of return strokes producing optically detectable surface arcing versus return stroke peak current, from the 1993 and 1995 experiments at Fort McClellan, Alabama, are shown in Fig. 2. As seen in Fig. 2, essentially all strokes with peak currents in excess of 15 kA or so produce optically detectable surface arcs. The surface arcing appears to be random in direction and often leaves little if any evidence on the ground. Even within the same flash, individual strokes can produce arcs developing in different directions. In one case it was possible to estimate the current carried by one arc branch which contacted instrumentation: approximately 1 kA or 5% of the total current peak in that stroke (Fisher et al. 1994). The observed horizontal extent of surface arcs was up to 20 m, which was the limit of photographic coverage during the 1993 Fort McClellan experiment. No fulgurites (see, for example, Rakov 1999) were found in the soil (red clay) at Fort McClellan, only concentrated current exit points at several spots along the 0.3- or 1.3-m steel grounding rod.

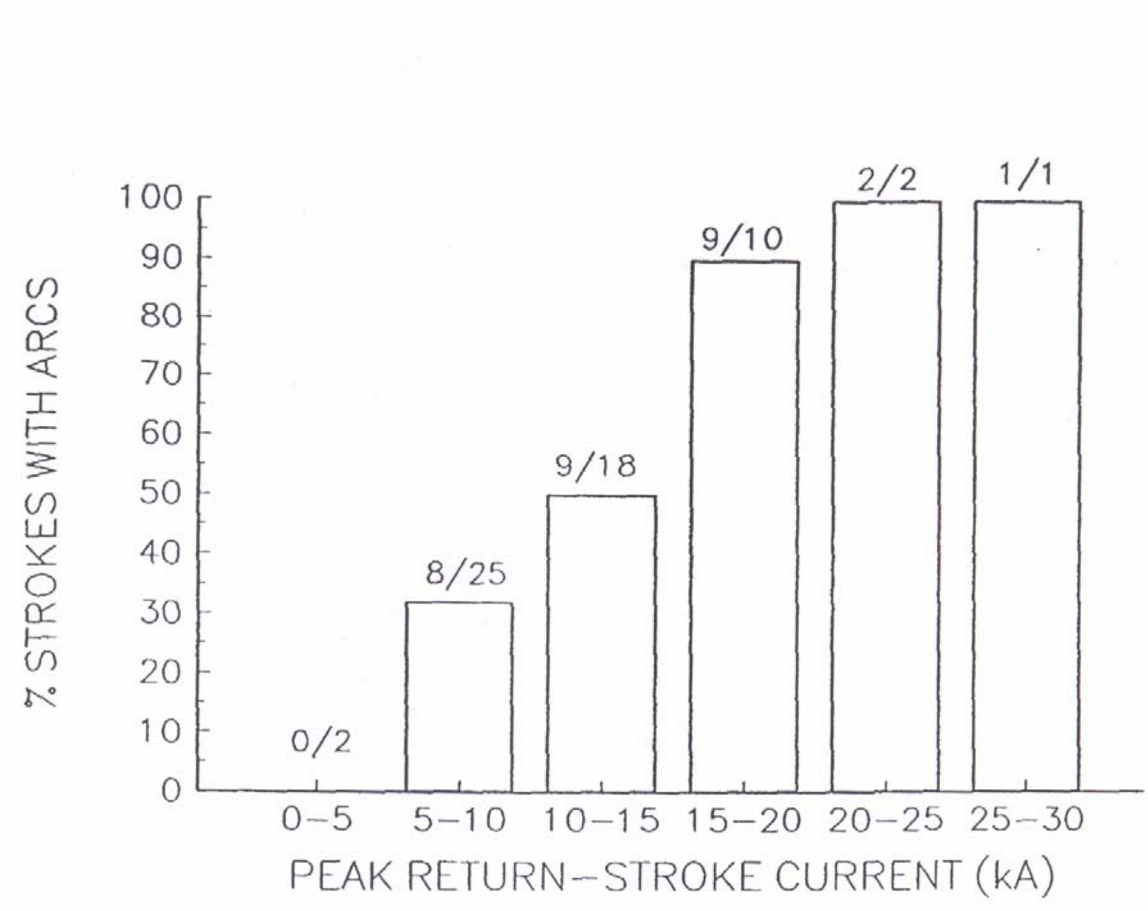


Fig. 2. Percentages of return strokes producing optically detectable surface arcs as a function of return stroke peak current (Fort McClellan, Alabama, 1993 and 1995). Numbers above each histogram column indicate the number of strokes producing optically detectable arcs (numerator) and the total number of strokes in that return stroke current range (denominator). Adapted from Rakov et al. (1998).

REFERENCES

Fisher, R.J., Schnetzer, G.H., and Morris, M.E., Measured Fields and Earth Potentials at 10 and 20 meters from the Base of Triggered-Lightning Channels, *Proc. 22nd Int. Conf. on Lightning Protection*, Budapest, Hungary, Paper R 1c-10, 6 p, 1994.

Holle, R.L., Lopez, R.E., and Zimmerman, C., Updated Recommendations for Lightning Safety, *Bull. Am. Meteor. Soc*. 80: 2035-41, 1999.

Installation Requirements for Lightning Protection Systems - UL96A (1998), *Underwriters Laboratories*, Northbrook, IL.

Kithil, R. and Rakov, V. Small Shelters and Safety from Lightning, *Golf Course Management*, 68: 104-12, 2000.

NFPA 780, Standard for the Installation of Lightning Protection Systems (1997), *National Fire Protection Association*, Quincy, MA.

Rakov, V.A., Lightning Makes Glass, *Journal of the Glass Art Society*, pp. 45-50, 1999.

Rakov, V.A., Uman, M.A., and Thottappillil, R. Review of Lightning Properties from Electric Field and TV Observations, *J. Geophys. Res*., 99: 10,745-50, 1994.

Rakov, V.A., Uman, M.A., Rambo, K.J., Fernandez, M.I., Fisher, R.J., Schnetzer, G.H., Thottappillil, R., Eybert-Berard, A., Berlandis, J.P., Lalande, P., Bonamy, A., Laroche, P., and Bondiou-Clergerie, A. New Insights Into Lightning Processes Gained from Triggered-Lightning Experiments in Florida and Alabama, *J. Geophys. Res*. 103: 14,117-30, 1998.